REDIRECTING FEEDTHROUGH LENS ANTENNA SYSTEM AND RELATED METHODS

Cross-Reference to Related Applications

[0001] This application is a continuation-in-part of U.S. Application No. 10/634,036, filed August 4, 2003, which is hereby incorporated herein in its entirety by reference.

Field of the Invention

[0002] The present invention relates to the field of communications systems, and more particularly, to phased array antennas.

Background of the Invention

[0003] Existing microwave antennas include a wide variety of configurations for various applications, such as satellite reception, remote broadcasting, or military communication. The desirable characteristics of low cost, light weight, low profile and mass producibility are provided in general by printed circuit antennas. The simplest forms of printed circuit antennas are microstrip

antennas wherein flat conductive elements, such as monopole or dipole antenna elements, are spaced from a single essentially continuous ground plane by a dielectric sheet of uniform thickness. An example of a microstrip antenna is disclosed in U.S. Patent No. 3,995,277 to Olyphant.

[0004] The antennas are designed in an array and may be used for communication systems such as identification of friend/foe (IFF) systems, personal communication service (PCS) systems, satellite communication systems, and aerospace systems, which require such characteristics as low cost, light weight, low profile, and a low sidelobe. The bandwidth and directivity capabilities of such antennas, however, can be limiting for certain applications.

[0005] The use of electromagnetically coupled dipole antenna elements can increase bandwidth. Also, the use of an array of dipole antenna elements can improve directivity by providing a predetermined maximum scan angle.

[0006] However, utilizing an array of dipole antenna elements presents a dilemma. The maximum grating lobe free scan angle can be increased if the dipole antenna elements are spaced closer together, but a closer spacing can increase undesirable coupling between the elements, thereby degrading performance. This undesirable coupling changes rapidly as the frequency varies, making it difficult to maintain a wide bandwidth.

[0007] One approach for compensating the undesirable coupling between dipole antenna elements is disclosed in U.S. Patent No. 6,417,813 to Durham, which is hereby

incorporated herein in its entirety by reference, and which is assigned to the current Assignee of the present invention. This patent discloses a wideband phased array antenna comprising an array of dipole antenna elements, with each dipole antenna element comprising a medial feed portion and a pair of legs extending outwardly therefrom.

[0008] In particular, adjacent legs of adjacent dipole antenna elements include respective spaced apart end portions having predetermined shapes and relative positioning to provide increased capacitive coupling between the adjacent dipole antenna elements. The increased capacitive coupling counters the inherent inductance of the closely spaced dipole antenna elements, in such a manner as the frequency varies so that a wide bandwidth may be maintained.

[0009] The above-noted patent further teaches that the benefits of such phased array antennas may be extended to a feedthrough lens antenna configuration, in which two such antennas are coupled together in back-to-back relationship. Such an antenna advantageously allows signals to pass through objects which would otherwise obstruct or degrade the signals (e.g., walls) without being substantially affected. Yet, despite the advantages provided by such arrangements, further feedthrough lens antenna control features may be desirable in certain applications.

Summary of the Invention

[0010] In view of the foregoing background, it is therefore an object of the present invention to provide a

feedthrough lens antenna system with enhanced control features and related methods.

[0011] This and other objects, features, and advantages in accordance with the present invention are provided by a redirecting feedthrough lens antenna system which may include first and second phased array antennas coupled together in back-to-back relation. More particularly, the first and second phased array antennas may include respective first and second arrays of dipole antenna elements thereon, where each dipole antenna element may include a medial feed portion and a pair of legs extending outwardly therefrom. The system may also include a respective phase shifter connected between each pair of back-to-back dipole antenna elements of the first and second dipole antenna arrays. Furthermore, a controller may be included for cooperating with the phase shifters to cause a signal received by the first phased array antenna at a first angle to be transmitted from the second phased array antenna at a redirected second angle different from the first angle.

[0012] In addition, the feedthrough lens antenna system may further include a respective gain element also connected between each pair of back-to-back dipole antenna elements of the first and second dipole antenna arrays. The controller may also control a gain of the gain elements. Moreover, the phase shifters and gain elements connected between each pair of back-to-back dipole antenna elements of the first and second dipole antenna arrays may be connected in series.

[0013] By way of example, adjacent legs of adjacent dipole antenna elements may include respective spaced

apart end portions. More particularly, the spaced apart end portions may have predetermined shapes and relative positioning to provide increased capacitive coupling between the adjacent dipole antenna elements. The system may also include a respective impedance element electrically connected between the spaced apart end portions of adjacent legs of adjacent dipole antenna elements. The impedance elements may be capacitors or inductors, for example. Also, the system may include a ground plane adjacent the first and second dipole element arrays.

[0014] A method aspect of the invention is for using a redirecting feedthrough lens antenna system, such as the one described briefly above. The method may include controlling the phase shifters to cause a signal received by the first phased array antenna at a first angle to be transmitted from the second phased array antenna at a redirected second angle different from the first angle.

Brief Description of the Drawings

[0015] FIG. 1 is top plan view of a building partly in sectional illustrating a redirecting feedthrough lens antenna system according to the present invention positioned in a wall of the building.

[0016] FIG. 2 is an exploded view of a phased array antenna of the redirecting feedthrough lens antenna system of FIG. 1.

[0017] FIG. 3 is a schematic diagram of the printed conductive layer of the phased array antenna of FIG. 2.

[0018] FIGS. 4A through 4D are enlarged schematic views of various spaced apart end portion configurations

of adjacent legs of adjacent dipole antenna elements of the wideband phased array antenna of FIG. 2.

[0019] FIG. 5 a schematic diagram of the printed conductive layer of another embodiment of the wideband phased array antenna of FIG. 2.

[0020] FIG. 6 is a schematic block diagram illustrating the redirecting feedthrough lens antenna of FIG. 1 in greater detail.

Detailed Description of the Preferred Embodiments

[0021] The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout, and prime and multiple prime notation are used to indicate similar elements in alternate embodiments.

[0022] Referring initially to FIG. 1, a redirecting feedthrough lens antenna system **60** according to the present invention is first described. As noted above, feedthrough lens antennas may be used in a variety of applications where it is desired to replicate an EM environment within a structure, such as a building **62**, over a particular bandwidth. For example, the redirecting feedthrough lens antenna system **60** may be positioned on a wall **61** of the building **62**. Of course, it will be

appreciated that the redirecting feedthrough lens antenna system **60** may be used on other structures as well, such as the wall of a ship, for example, or in other applications where it is desirous to pass a signal through a structure that would otherwise obstruct or degrade the signal.

[0023] As illustratively shown in FIG. 1, the redirecting feedthrough lens antenna system **60** allows EM signals **63** from a transmitter **80** (e.g., a cellular telephone base station) to be replicated and redirected within the interior of the building **62** and received by a receiver **81** (e.g., a cellular telephone), as will be discussed further below.

[0024] The feedthrough lens antenna system **60** illustratively includes first and second phased array antennas **10a, 10b**, which are preferably substantially identical. Generally speaking, the redirecting feedthrough lens antenna system **60** causes the EM signals **63** received by the first phased array antenna **10a** at a first angle θ_1 to be transmitted from the second phased array antenna **10b** at a second angle θ_2 different from the first angle. For clarity of explanation, prior to describing the redirection features of the redirecting feedthrough lens antenna system **60**, a single phased array antenna **10** will first be described with reference to FIGS. 2-5.

[0025] The wideband phased array antenna **10** is preferably formed of a plurality of flexible layers, as shown in FIG. 2. These layers include a dipole layer **20**, or current sheet, which is sandwiched between a ground plane **30** and a cap layer **28**. Additionally, dielectric

layers of foam **24** and an outer dielectric layer of foam **26** are provided. Respective adhesive layers **22** secure the dipole layer **20**, ground plane **30**, cap layer **28**, and dielectric layers of foam **24, 26** together to form the flexible and conformal antenna **10**. Of course, other ways of securing the layers may also be used, as will be appreciated by the skilled artisan.

[0026] The dielectric layers **24, 26** may have tapered dielectric constants to improve the scan angle. For example, the dielectric layer **24** between the ground plane **30** and the dipole layer **20** may have a dielectric constant of 3.0, the dielectric layer **24** on the opposite side of the dipole layer **20** may have a dielectric constant of 1.7, and the outer dielectric layer **26** may have a dielectric constant of 1.2. It should be noted that other approaches may also be used to make the antenna **10** operate without the upper dielectric layers **24, 26**. However, generally speaking it is typically desirable to include the dielectric layers **24, 26** above the layer **20**.

[0027] Referring now to FIGS. 3, 4A and 4B, a first embodiment of the dipole layer **20** will now be described. The dipole layer **20** is a printed conductive layer having an array of dipole antenna elements **40** on a flexible substrate **23**. Each dipole antenna element **40** comprises a medial feed portion **42** and a pair of legs **44** extending outwardly therefrom. Respective feed lines are connected to each feed portion **42** from the opposite side of the substrate, as will be described in greater detail below. Adjacent legs **44** of adjacent dipole antenna elements **40** have respective spaced apart end portions **46** to provide increased capacitive coupling between the

adjacent dipole antenna elements. The adjacent dipole antenna elements **40** have predetermined shapes and relative positioning to provide the increased capacitive coupling. For example, the capacitance between adjacent dipole antenna elements **40** may be between about 0.016 and 0.636 picofarads (pF), and preferably between 0.159 and 0.239 pF.

[0028] Preferably, as shown in FIG. 4A, the spaced apart end portions **46** in adjacent legs **44** have overlapping or interdigitated portions **47**, and each leg **44** comprises an elongated body portion **49**, an enlarged width end portion **51** connected to an end of the elongated body portion. Each leg **44** further comprises a plurality of fingers **53** (e.g., four) extending outwardly from the enlarged width end portion.

[0029] Alternatively, as shown in FIG. 4B, adjacent legs **44'** of adjacent dipole antenna elements **40'** may have respective spaced apart end portions **46'** to provide increased capacitive coupling between the adjacent dipole antenna elements. In this embodiment, the spaced apart end portions **46'** in adjacent legs **44'** comprise enlarged width end portions **51'** connected to an end of the elongated body portion **49'** to provide the increased capacitance coupling between the adjacent dipole antenna elements. Here, for example, the distance K between the spaced apart end portions **46'** is about .003 inches. Of course, other arrangements which increase the capacitive coupling between the adjacent dipole antenna elements are also contemplated by the present invention.

[0030] By way of example, to further increase the capacitive coupling between adjacent dipole antenna

elements **40**, a respective discrete or bulk impedance element may be electrically connected across the spaced apart end portions of adjacent legs **44"** of adjacent dipole antenna elements, as illustrated in FIG. 4C. In the illustrated embodiment, the spaced apart end portions **46″** have the same width as the elongated body portions connected to an end of the elongated body portions **49″**.

[0031] The discrete impedance elements **70″** are preferably soldered in place after the dipole antenna elements **40** have been formed so that they overlay the respective adjacent legs **44″** of adjacent dipole antenna elements **40**. This advantageously allows the same capacitance to be provided in a smaller area, which helps to lower the operating frequency of the phased array antenna **10**.

[0032] The illustrated discrete impedance element includes a capacitor **72″** and an inductor **74″** connected together in series. However, other configurations of the capacitor **72″** and inductor **74″** are possible, as will be readily appreciated by those skilled in the art. For example, the capacitor **72″** and an inductor **74″** may be connected together in parallel, or the discrete impedance element **70″** may include the capacitor without the inductor or the inductor without the capacitor. Depending on the intended application, the discrete impedance element **70″** may even include a resistor.

[0033] The discrete impedance element **70″** may also be connected between the adjacent legs **44** with the overlapping or interdigitated portions **47** illustrated in FIG. 4A. In this configuration, the discrete impedance element **70″** advantageously provides a lower cross

polarization in the antenna patterns by eliminating asymmetric currents which flow in the interdigitated capacitor portions **47**. Likewise, the discrete impedance element **70″** may also be connected between the adjacent legs **44″** with the enlarged width end portions **51′** illustrated in FIG. 4B.

[0034] Another advantage of the respective discrete impedance elements **70″** is that they may have impedance values so that the bandwidth of the phased array antenna **10** can be tuned for different applications, as would be readily appreciated by those skilled in the art. In addition, the impedance is not dependent on the impedance properties of the adjacent dielectric layers **24** and adhesives **22**. Since the discrete impedance elements **70″** are not effected by the dielectric layers **24**, this approach advantageously allows the impedance between the dielectric layers **24** and the impedance of the discrete impedance element **70″** to be decoupled from one another.

[0035] Yet another approach to further increase the capacitive coupling between adjacent dipole antenna elements **40** includes placing a respective printed impedance element **80″′** adjacent the spaced apart end portions of adjacent legs **44″′** of adjacent dipole antenna elements **40**, as illustrated in FIG. 4D. The respective printed impedance elements are separated from the adjacent legs **44″′** by a dielectric layer, and are preferably formed before the dipole antenna layer **20** is formed so that they underlie adjacent legs **44″′** of the adjacent dipole antenna elements **40**.

[0036] Alternately, the respective printed impedance elements **80″′** may be formed after the dipole antenna

layer **20** has been formed. For a more detailed explanation of the printed impedance elements and antenna element configurations, reference is directed to U.S. Patent Application Serial No. 10/308,424, which is assigned to the current Assignee of the present invention and is hereby incorporated herein in its entirety by reference, as well as to the above-noted U.S. Patent Application Serial No. 10/634,036.

[0037] Preferably, the array of dipole antenna elements **40** are arranged at a density in a range of about 100 to 900 per square foot. The array of dipole antenna elements **40** are sized and relatively positioned so that the phased array antenna **10** is operable over frequency range of about 2 to 30 GHz, and at a scan angle of about ±60 degrees (low scan loss). Such an antenna **10** may also have a 10:1 or greater bandwidth, includes conformal surface mounting, while being relatively lightweight, and easy to manufacture at a low cost.

[0038] For example, FIG. 4A is a greatly enlarged view showing adjacent legs **44** of adjacent dipole antenna elements **40** having respective spaced apart end portions **46** to provide the increased capacitive coupling between the adjacent dipole antenna elements. In the example, the adjacent legs **44** and respective spaced apart end portions **46** may have the following dimensions: the length E of the enlarged width end portion **51** equals 0.061 inches; the width F of the elongated body portions **49** equals 0.034 inches; the combined width G of adjacent enlarged width end portions **51** equals 0.044 inches; the combined length H of the adjacent legs **44** equals 0.276 inches; the width I of each of the plurality of fingers **53** equals 0.005

inches; and the spacing J between adjacent fingers **53** equals 0.003 inches.

[0039] In the example (referring to FIG. 3), the dipole layer **20** may have the following dimensions: a width A of twelve inches and a height B of eighteen inches. In this example, the number C of dipole antenna elements **40** along the width A equals 43, and the number D of dipole antenna elements along the length B equals 65, resulting in an array of 2795 dipole antenna elements. The wideband phased array antenna **10** has a desired frequency range, e.g., 2 GHz to 18 GHz, and the spacing between the end portions **46** of adjacent legs **44** is less than about one-half a wavelength of a highest desired frequency.

[0040] Referring to FIG. 5, another embodiment of the dipole layer **20'** may include first and second sets of dipole antenna elements **40** which are orthogonal to each other to provide dual polarization, as will be appreciated by the skilled artisan. The phased array antenna **10** may be made by forming the array of dipole antenna elements **40** on the flexible substrate **23**. This preferably includes printing and/or etching a conductive layer of dipole antenna elements **40** on the substrate **23**. As shown in FIG. 5, first and second sets of dipole antenna elements **40** may be formed orthogonal to each other to provide dual polarization.

[0041] Again, each dipole antenna element **40** includes the medial feed portion **42** and the pair of legs **44** extending outwardly therefrom. Forming the array of dipole antenna elements **40** includes shaping and positioning respective spaced apart end portions **46** of

adjacent legs **44** of adjacent dipole antenna elements to provide increased capacitive coupling between the adjacent dipole antenna elements. Shaping and positioning the respective spaced apart end portions **46** may include forming interdigitated portions **47** (FIG. 4A) or enlarged width end portions **51'** (FIG. 4B), etc. A ground plane **30** is preferably formed adjacent the array of dipole antenna elements **40**, and one or more dielectric layers **24**, **26** are layered on both sides of the dipole layer **20** with adhesive layers **22** therebetween.

[0042] Forming the array of dipole antenna elements **40** may further include forming each leg **44** with an elongated body portion **49**, an enlarged width end portion **51** connected to an end of the elongated body portion, and a plurality of fingers **53** extending outwardly from the enlarged width end portion. Again, the wideband phased array antenna **10** has a desired frequency range, and the spacing between the end portions **46** of adjacent legs **44** is less than about one-half a wavelength of a highest desired frequency. The ground plane **30** is spaced from the array of dipole antenna elements **40** less than about one-half a wavelength of the highest desired frequency.

[0043] As discussed above, the array of dipole antenna elements **40** are preferably sized and relatively positioned so that the wideband phased array antenna **10** is operable over a frequency range of about 2 GHz to 30 GHz, and operable over a scan angle of about ±60 degrees. The antenna **10** may also be mounted on a rigid mounting member **12** having a non-planar three-dimensional shape, such as an aircraft, for example.

[0044] Thus, a phased array antenna **10** with a wide frequency bandwidth and a wide scan angle is obtained by utilizing tightly packed dipole antenna elements **40** with large mutual capacitive coupling. Conventional approaches have sought to reduce mutual coupling between dipoles, but the present invention makes use of, and increases, mutual coupling between the closely spaced dipole antenna elements to prevent grating lobes and achieve the wide bandwidth. The antenna **10** is scannable with a beam former, and each antenna dipole element **40** has a wide beam width. The layout of the elements **40** could be adjusted on the flexible substrate **23** or printed circuit board, or the beam former may be used to adjust the path lengths of the elements to put them in phase.

[0045] Turning additionally to FIG. 6, the redirecting feedthrough lens antenna system **60** will now be further described. As noted above, the system **60** includes the first and second phased array antennas **10a, 10b** coupled together in back-to-back relation, each of which includes an array of antenna elements **40** thereon. The system **60** also illustratively includes a respective phase shifter **85** connected between each pair of back-to-back dipole antenna elements **40a, 40b** of the first and second dipole antenna arrays, although only a single pair of antenna elements and the respective phase shifter **85** therefor is shown for clarity of illustration.

[0046] Furthermore, a controller **86** cooperates with the phase shifters **85** to cause a signal received by the first phased array antenna **10a** at the first angle θ_1 to be transmitted from the second phased array antenna **10b** at a redirected second angle θ_2 different from the first angle,

as will be appreciated by those skilled in the art. It will also be appreciated by those skilled in the art that the various phase control operations performed by the controller **85** may in some embodiments be spread across multiple controllers arranged in a hierarchy. This approach may be particularly advantageous for larger antenna arrays, for example.

[0047] The redirecting feedthrough lens antenna system **60** may further include a respective gain element **87** also connected between each pair of back-to-back dipole antenna elements **40a, 40b** of the first and second dipole antenna arrays, and the controller **86** may similarly control a gain of the gain elements. Moreover, the phase shifters **85** and gain elements **87** between each pair of back-to-back dipole antenna arrays **40a, 40b** may be connected in series, as shown. In particular, the antenna elements **40a, 40b**, phase shifter **85**, and gain element **87** may be connected by transmission elements **88**, which may be coaxial cables, for example. Of course, other suitable feed structures known to those of skill in the art may also be used as well.

[0048] Additionally, the phase shifters **85** and gain elements **87** may be positioned between (or within) the ground planes **30a, 30b** of the first and second phased array antennas **10a, 10b**. Further details regarding suitable coupling structures for connecting the first and second phased array antennas **10a, 10b** in a back-to-back relationship may be found in the above-noted U.S. Patent No. 6,417,813.

[0049] It should also be noted that there can be different geometrical arrangements of dipole elements **40**

that can provide for the transmission or rejection of polarized waves. The system **60** may be configured with an arrangement of dipole elements **40** oriented in one direction, providing a single linear polarization (the terms "vertical" or "horizontal" are often used but a single linear polarization may have any orientation relative to a given reference angle) or may include crossed dipoles which would provide for a more general antenna solution. Crossed dipoles, nominally oriented at ninety degrees to one another (see FIG. 5), provide two basis vectors from which any sense linear or elliptical polarization may be formed with appropriate phasing of the elements, as will be appreciated by those skilled in the art. Of course, other geometrical or element arrangements for polarization control may also be used, as will also be appreciated by those skilled in the art.

[0050] Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and embodiments are intended to be included within the scope of the appended claims.